A LOW COST SINGLE SIDEBAND MULTIPLEX SYSTEM

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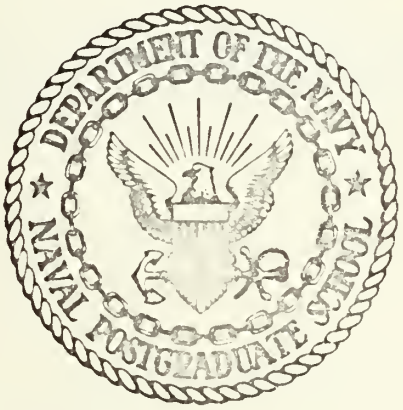

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THESIS

A LOW COST SINGLE SIDEBAND MULTIPLEX SYSTEM

by

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September 1971

Approved for public release; distribution unlimited.

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A Low Cost Single Sideband Multiplex System

by

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Ensign, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September 1971

ABSTRACT

A thirty channel low cost single sideband multiplex system is presented. This design is specifically tailored for microwave communications by small businesses desiring inexpensive, high quality communication links. One channel was built and tested in the laboratory and the results are included. A major factor in the low cost of this system without compromising performance was the availability of inexpensive mechanical filters. Synchronization is a major feature of this system using injected carrier to maintain phase-lock.

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ACKNOWLEDGEMENTS

The encouragement and invaluable assistance continually offered by advisor, Dr. Gerald D. Ewing, and the help and equipment offered by LCDR Ray Belanger, USN, is gratefully acknowledged.

I. INTRODUCTION

Many businesses requiring communication links with their subsidiaries today have an option of perhaps utilizing commercial microwave relay networks for this service instead of going to the telephone company. It would be economically advantageous for business to use the least expensive communication system. Presented is a design for a single sideband multiplex system. It was designed specifically for microwave communications by small businesses desiring inexpensive, high quality communication links. The development of multiplex telephony is traced up to the present. Integral to actual implementation of the system but not a part of the design is certain auxiliary equipment such as a hybrid and a power supply.

The major contributing factor in the cost of this system was the availability of low cost mechanical filters. They are competitive with certain ceramic filters currently in use. Advantage was made of the filter's excellent selectivity by using it for sideband selection.

Incorporated in the design for this system was synchronization. Injected carrier detected in the receiver is used to keep the system in phase-lock. This increases the flexibility of the system by allowing it to be used for a much wider range of applications.

II. DEVELOPMENT OF MULTIPLEX TELEPHONY

Multiplex telephone communications has been marked with many milestones beginning with Alexander Graham Bell's invention of the telephone in 1876. From Bell's crude apparatus to today's complex intercontinental systems, telephone communications has steadily improved, providing better, faster and more economical service.

The first practical circuits were a single grounded wire with a telephone at each end. They were very limited in that a telephone could only be connected to one telephone at the other end. There was no means for interconnecting different telephones.

The first telephone exchange for interconnecting telephones opened January 28, 1878, in New Haven, Connecticut. It connected 21 telephones over eight open-wire lines called subscriber loops. Service was extended by interconnecting local offices with extra lines called trunks. Those connecting local offices were called exchange trunks while those used for long distance were named toll trunks.

Techniques used in the single open-wire technology had been borrowed from telegraphy, but it had inherent problems such as noise and crosstalk. These problems were solved by the two-wire or metal circuit which had one wire providing a return. It solved the interference problem found in the single open-wire, but it presented the telephone industry with the tremendous task of doubling a telephone system that was nearly overburdened already. Across

the country telephone poles loaded with crossarms carrying hundreds of wires lined all the major streets and roads. This unenviable task was completed between 1890 and 1900 with many of the wires being wound into cables, but it was clear a better system was needed.

The solution to this proved to be multiplexing. It was found early that a bandwidth from 300-2800 hertz was needed for sufficient fidelity and clarity for modern voice communication. Since it was possible to transmit higher frequencies over wires, the telephone system was not being optimally used. Multiplexing is a means whereby more than one signal can be transmitted over wires. It even predates the telephone, with Bell experimenting with telegraph multiplexing prior to inventing the telephone.

Vibrating reeds were used at first for multiplexing because with the early state-of-the-art, there were not sufficient electronic devices. They were called harmonic telegraph systems with carriers of only a few hundred hertz. Multiplexing awaited the advance of radio technology slightly before 1900 with the invention of the vacuum tube by Edison, the grid by Deforest, and the improvement of electrical filters between 1900 and 1910. In 1910 Major G. O. Squier, an Army officer in the Signal Corps, developed an experimental multiplex system which was operated over a short length. Renewed interest in multiplex telephony was sparked as a result, particularly in the Bell system.

In order for two or more signals to be transmitted over the same line, they must be separated somehow to prevent

interference from other signals. There are two methods for accomplishing this. They can be separated in frequency, known as frequency division multiplexing; or they may be separated in time, known as time division multiplexing. While both methods of transmission were tested in the early stages of multiplex telephony, frequency division multiplexing became more prevalent.

Either frequency or amplitude modulation is used to transform the speech information to the carrier frequency with amplitude modulation being the more common method. The amplitude modulated signal consists of a carrier wave, an upper sideband (USB) wave, and a lower sideband (LSB) wave. The two sidebands are separated from the carrier on either side by a frequency equal to the modulating speech signal. Each sideband contains all the information of the signal. Since this is a redundancy, only one sideband is needed. The carrier obviously carries no information so that one sideband and the carrier can be suppressed as long as the carrier is reinserted in the receiver to demodulate the signal. With only one sideband being transmitted and the carrier suppressed, only half the bandwidth of the normal amplitude modulated signal is needed and less energy is required. Thus, in the multiplex frequency band twice the number of channels with less energy can be transmitted with single sideband, suppressed-carrier than with amplitude modulation. Sometimes the carrier is reinserted at a low level as a reference. Single-sideband (SSB) with the carrier

suppressed is used in most multiplex systems developed for toll circuit use.

The basic components of a frequency division multiplex system utilizing single-sideband, suppressed carrier (SSSC) are modulators and demodulators, filters, and a carrier frequency source. Additional circuitry needed is that included for signalling, power and regulation. Consider frequency division multiplexing (FDM) in its simplest form. Voice signals from the telephone associated with each channel are fed through a low-pass filter which limits frequencies to those below about 4000 Hz to conserve the frequency spectrum. The frequency limited signal is passed to a balanced modulator where it modulates the carrier frequency. A balanced modulator balances out or suppresses the carrier frequency leaving only the upper and lower sidebands. A band-pass filter removes the unwanted sideband. This sideband is combined with other sideband signals and transmitted. At the receiving end a band-pass filter passes the desired sideband signal to a demodulator where a carrier identical to that injected at the transmitter balanced modulator mixes with the desired sideband signal. The output of the demodulator is fed through a low-pass filter to recover the voice signal while rejecting other unwanted signals.

The first commercial multiplex system began operation in 1918 between Baltimore, Maryland, and Pittsburgh, Pennsylvania, after the American Telephone and Telegraph Company demonstrated the economic feasibility of commercial multiplex

telephony with a laboratory model on open-wire line between South Bend, Indiana, and Toledo, Ohio, in 1914. The Bell System designated their original multiplex system type A. It provides four two-way channels for use over a single open-wire line with the same carrier frequency being used for each direction of transmission. It required hybrid coils to separate the transmit and receive signals. This feature proved to be objectionable as it allowed too much loop sing. Type A was followed by B in 1920 which provided three two-way channels using different frequencies for each direction of transmission. A filter separated the channel transmit and receive signals, and no hybrid was needed. This technique of using different frequencies for each direction of transmission is known as an equivalent four-wire system. Both types A and B used amplitude modulation with A transmitting SSSC and B transmitting SSB with carrier. Naturally, when the type C system was developed about 1925, it incorporated the best of types A and B; that is, three channels with different frequencies for each direction using SSSC.

These early systems utilized the frequency band from 10 to 30 Khz with telegraphy being allocated the band below 10 Khz. Higher frequencies were not used because of crosstalk, higher attenuation, and problems associated with open-wire lines. Much research was conducted to completely measure and analyze line characteristics. Cable pairs were found to have more attenuation per unit length than open-wire pairs,

but open-wire pairs were found to be more prone to change with temperature, humidity and especially icing. Attenuation was proportional to frequency. Also, wire size and spacing affected the results. In general, at multiplex frequencies open-wire pairs are considered to have an impedance of 600 ohms; however, for non-loaded toll cable this value drops to approximately 130 ohms. These differences had a great affect on design requirements of early multiplex systems. In general, systems were designed for either open-wire or cable pairs but not both. By 1928 the type C developed into a transcontinental system along with other more limited systems.

The Bell System's type J was the first multiplex system to make use of new types of components. Along with standardization it also became more economical. Its 12 channels were designed for open-wire lines and had line frequencies from 36-140 Khz using 36-84 Khz in one direction and 92-140 Khz in the other. Combining the 12 channels of the type J, three from the type C, and one voice frequency circuit could provide 16 telephone channels on a single pair of wires. Type K, another 12 channel system, was put into service in 1938 on a transcontinental cable system. Type K used the frequency band from 12-60 Khz for transmission in both directions. This was done using a different pair of wires for each direction, establishing a physical four-wire system. It also introduced a new technique known as group modulation which resulted in lower line frequencies. In

earlier systems multiplex line frequencies were accomplished by a single direct modulation step whereas group modulation uses two or more steps of modulation to establish line frequencies. Group modulation provided an easy way for interconnecting standard subgroups. It was later used in the type M system.

Before World War II, the 12 channel J open-wire and 12 channel K cable systems provided the needed economy and circuit capacity on long and medium distance routes. They established multiplexing as the method for delivering toll circuits over long distances. Following the war, demand for short, medium and long distance telephone circuits continually increased. However, with a desperate shortage of materials, particularly copper, and with labor and material costs increasing, multiplex circuits for economical, short-haul use were needed. Such systems would, of necessity, have to be simply installed, operated, and maintained in addition to being competitive with voice frequency circuits.

The Bell System produced the type N with 12 channels over two cable pairs and the type O with four, four-channel groups over an open-wire. Lenkurt Electric developed its type 33A at this time, providing stackability. That is, individual channels could be added as needed vice multiplexing all channels at once.

The year 1952 brought forth the next major development with Lenkurt's type 45A system. This 12 channel system for

open-wire lines utilized miniaturization of solid state components and modular plug-in concepts in telephone multiplexing. The Bell System's type N3 and Lenkurt's type 46B are two of today's modern solid state frequency division multiplex systems, providing up to 24 channels with line frequencies varying from 36 to 264 Khz over standard types of toll cable. The line frequencies are different for each direction of transmission. These transistorized systems provide economical service for intertoll and toll-connecting trunks and other medium and short-haul applications.

Short-haul applications led multiplexing to its use in exchange trunks and subscriber loops. Such short-haul systems proved particularly suitable for rural and sparsely populated areas where one could provide adequate service to as many as 50 users. The Bell System developed the type T1 to compete with the cost of loaded cable pairs used for exchange trunks shorter than 10 miles. It is a time-division multiplex system which utilizes pulse-code modulation to provide 24 channels over an exchange trunk cable.

Following World War II, the Bell System developed wideband transmission using coaxial cable and microwave radio. The bandwidth of open-wire and multi-pair cable limits their capacity to about 16 channels for open-wire lines and 24 channels for multi-pair cable whereas coaxial cable and microwave radio operate with much wider bandwidths.

About 1948 the Bell System completed its first transcontinental coaxial cable transmission facility. Designated

type L1, it was capable of handling 600 single-sideband suppressed carrier frequency division multiplex telephone channels or one television channel. The L3 followed the L1 with a capacity of 1860 telephone channels or one television channel and 600 telephone channels. The type L4 coaxial cable system had a capacity of about 32,000 multiplex telephone channels or a corresponding television-telephone channel trade off. The type TD-2 or 3 and type TH are two long-haul microwave radio relay systems. Type TD-2 operates in the 4000 Mhz common-carrier band and is capable of handling 12,000 channels. The TH system is in the 6000 Mhz band with a capacity in excess of 11,000 channels [1].

The telephone industry has progressed at a considerable rate since Bell invented the telephone in 1876, and multiplexing has helped solve some of the problems of increased capacity with minimum increase in equipment. In the future are higher capacity systems that will use laser beams carrying multiplexed signals. In addition to high capacity systems, multiplexing techniques are being used to solve communications problems in industry and small businesses to provide private microwave links between plants and offices. In addition to carrying voice communications, many modern communications systems carry both high and low speed digital signals.

III. SYSTEM SPECIFICATIONS AND DESIGN CONSIDERATIONS

A. SPECIFICATIONS

Method of Transmission	Single-sideband with re-inserted carrier
Channel Capacity	1-30 Channels
Input Impedance	VF 600 ohms balanced HF 600 ohms
Output Impedance	VF 600 ohms HF 600 ohms
Frequencies	VF 0.3-3.0 Khz HF 4-124 Khz
Power Supply	-24 volts DC
Levels	
VF Test Tone Transmit	-16dBm
Receive	+ 7dBm adjustable
HF Line (per channel)	
Transmit	-29dBm
Receive	-29dBm
Signalling -	Accomplished by carrier interruption
Synchronization	
Environmental Conditions	0 - 50°C.

B. DESIGN CONSIDERATIONS

The primary consideration in the design of this multiplex system was cost. In order to make it competitive with existing systems, low cost was clearly a necessity. Much effort was expended toward this goal. For instance, expensive wideband transformers were avoided in the circuitry, but the single most important factor in the economic feasibility of this system was the availability of low cost mechanical filters. The total price of parts was kept below

$100 with approximately $25 additional to be used for labor. Plant overhead and other expenses would determine the retail price above this figure.

Traditionally, mechanical filters have been expensive by not lending themselves to mass production. The mechanical filter used in this system cost $27 each in small quantities. It was a standard item used in this system for sideband selection, and the system was designed essentially around it. Crystal frequencies were assigned to fall on its skirts. A similar mechanical filter was available from a Japanese manufacturer for less than half the price of the one used in this design. This makes the mechanical filter competitive with a Lenkurt crystal filter costing the Lenkurt Company $12 as quoted by a company representative in a seminar at the U. S. Naval Postgraduate School in the spring of 1971.

Provision was made with each channel's carrier oscillator to omit it from all but one channel per shelf in order for one channel to fulfill the carrier frequency requirements for all the channels on that shelf. To extend this to other shelves in a rack would so complicate shelf wiring as to make it impractical. Isolation is provided between any given oscillator and its users through the use of emitter followers.

A complete (duplex) channel consists of two circuit boards containing the transmit and receive functions. If the user desires only a simplex (either transmit or receive)

channel, only one circuit board would be needed. For each duplex channel there is only one channel and one carrier oscillator. On each circuit board provision is made for both channel and carrier oscillators. For a duplex channel, one channel and carrier oscillator would be packed with components, but the provision was made for them on both printed circuit boards for the case of the simplex channel. This would alleviate further board layout when a simplex channel was specified.

The components used in signalling and synchronization can be removed from the circuit boards when they are not specified. The user can have either synchronization or signalling without being committed to the other. The carrier pick-off filter, used in both synchronization and signalling, contains a crystal for high selectivity and narrow bandwidth, making it a considerable part of the cost in both synchronization and signalling. Because of this, there would very likely be few applications where only one of these functions would be specified without the other.

Major components of the synchronization include a common, low cost 455 Khz IF transformer and an integrated circuit operational amplifier. A prime consideration was the availability of inexpensive varicaps. Without synchronization a crystal oven might be required, making the cost almost as much as synchronization with reduced performance.

The signalling circuitry also uses the carrier pick-off filter, but beyond that, the only major component is one relay.

Because the cost of signalling is not a major factor, it would generally be specified by the user.

When selecting components, one inexpensive transistor was chosen to be used throughout the design, making assembly simpler. Circuits were designed to be relatively insensitive to transistor parameters. It was possible to avoid wideband transformers to help decrease the cost of the balanced modulators. Integrated circuits were rejected because certain customers (perhaps foreign) would not be able to replace them easily.

IV. THEORY OF OPERATION

A. GENERAL

The individual channels consist of four principal parts. They are the transmit, receive, synchronization, and signalling functions. A block diagram is shown in Figure 1. The transmitter accepts the signal, processes it by forming a single-sideband signal translated up to the channel frequency, and places it on a baseband. The receiver retrieves the signal for the user. Signalling allows dialing pulses to be transmitted and received. Synchronization keeps input and output frequencies in phase-lock. This is important for tone transmission as used by some processing industries. Both transmit and receive functions have input and output impedances of 600 ohms for impedance matching.

B. TRANSMIT

An amplifier feeds the input signal (voice or data) to a balanced modulator where a double sideband signal is produced (see Appendix A). A mechanical filter with center frequency 455 Khz (see Appendix C) passes the upper sideband while rejecting the lower sideband and any residual carrier. The signal enters a second balanced modulator with some of the carrier frequency which has been injected. Mixing with the channel frequency, the desired output of the balanced modulator is the difference frequency. A balanced modulator is used to suppress the channel frequency to keep it at a low level on the baseband. The signal, which is now in a

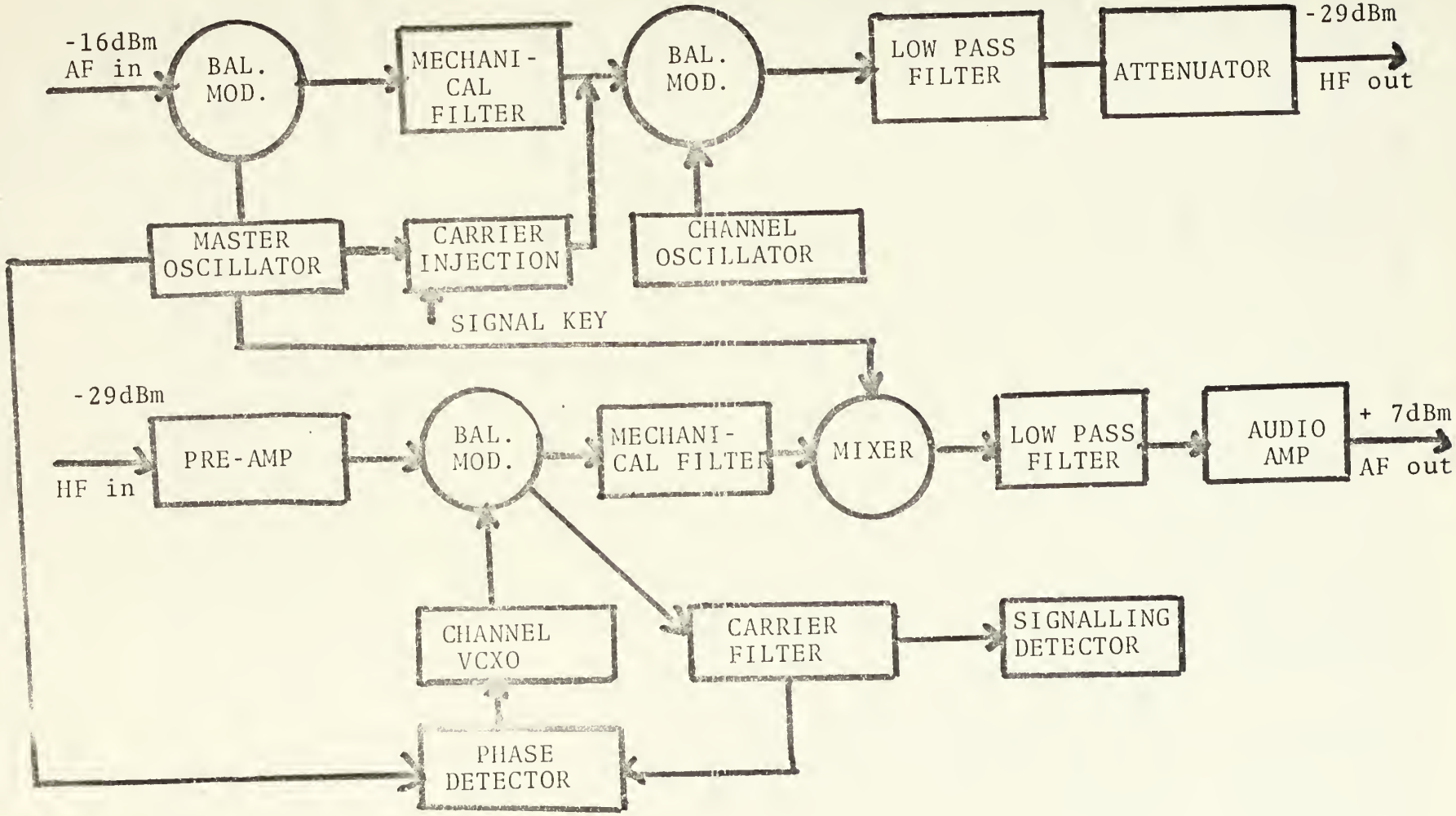


Figure 1. System Block Diagram.

unique position in the frequency domain determined by the channel oscillator frequency, passes through a low-pass filter which rejects frequencies greater than the highest channel frequency. The signal is then placed on the base-band with the proper level and impedance.

As an example, a voice signal in the first balanced modulator of the transmitter would mix with the carrier frequency of 453.35 Khz (see Appendix B) to produce (453.35 + USB), (453.35 - LSB)Khz and harmonics. The mechanical filter passes the upper sideband. The 453.35 Khz frequency itself has been suppressed in the balanced modulator and further suppressed by the mechanical filter. The 453.35 Khz carrier frequency is injected in a controlled amount following the mechanical filter. The combined signal enters a second balanced modulator where it mixes with the channel one frequency of 461.35 Khz in this case. The desired outputs are the difference frequencies, or:

$$461.35 - (453.35 + USB) = 8 \text{ Khz} - USB.$$

These steps are shown in Figure 2. The other channels occur every 4 Khz up to the highest (30th channel) where the frequencies are (124.35 - USB). In the actual circuitry the only difference between channels is the channel oscillator crystal so that channel selection is determined solely by crystal selection.

C. RECEIVE

An amplifier feeds a balanced modulator where a channel frequency is mixed all the incoming signals. The desired

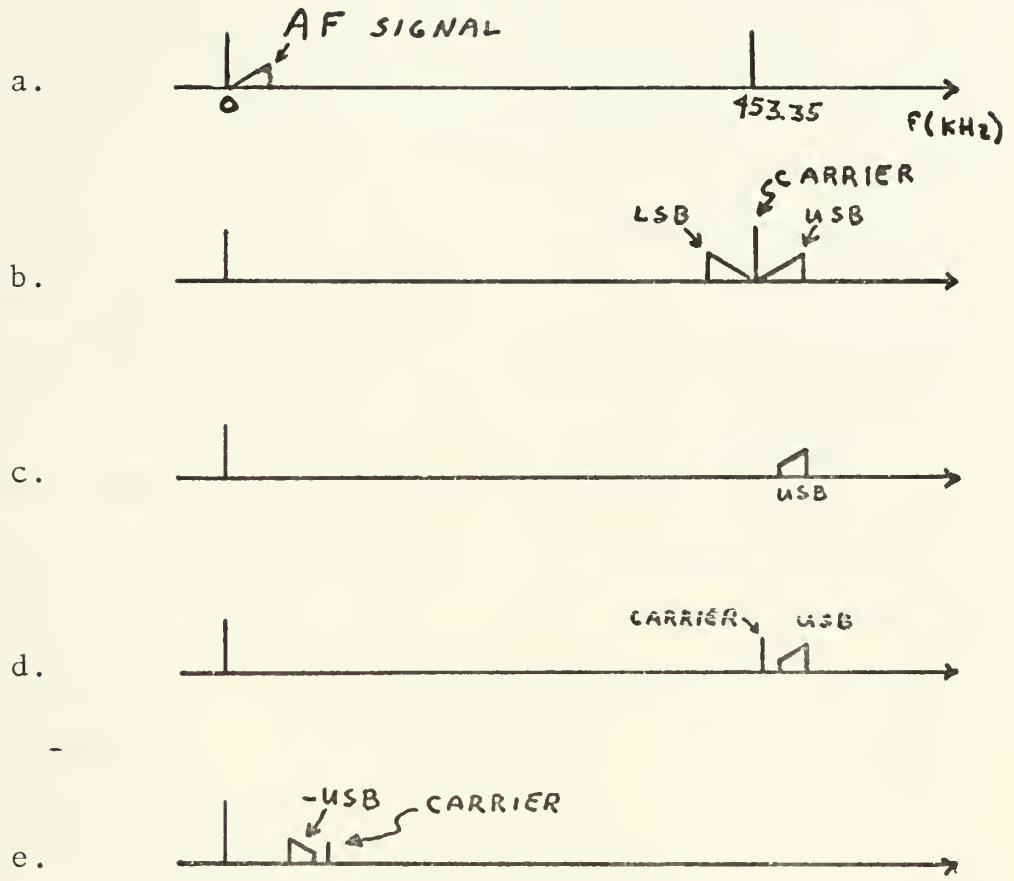


Figure 2. Transmit frequency translation operations; a. Input signals, b. Output of balanced modulator (DSB signal), c. Output of mechanical filter, d. Signal with reinserted carrier, e. Signal in channel position on baseband.

output is the difference frequency which would be the carrier frequency plus the USB. The carrier frequency is detected and amplified by the carrier pick-off filter, and the USB is passed through the mechanical filter, rejecting the carrier frequency and other unwanted signals. The USB mixes with the carrier frequency to produce the original band-limited signal. A low-pass filter rejects out of band frequencies, the signal is amplified with gain control, and it is then delivered to the user.

Continuing the example of the first channel, the first channel (8 Khz - USB), in addition to other signals on the baseband, mixes with 461.35 Khz to produce (453.35 + USB) Khz plus other unwanted signals. The carrier pick-off filter detects the carrier, and the USB is passed through the mechanical filter. In the mixer the USB mixes with the carrier to reproduce the original signal. These steps are illustrated in Figure 3.

D. SYNCHRONIZATION

Synchronization is a requirement for coherent digital transmissions and for tone telemetry. The received signal frequencies must be the same as those transmitted. Without it greater care would be needed to insure close tolerances in the crystals such as crystal ovens for voice communications and non-coherent digital transmissions. The difference between transmitted and received audio frequencies should be less than 2 hertz, but more could be tolerated for voice transmissions. Synchronization is accomplished with the aid

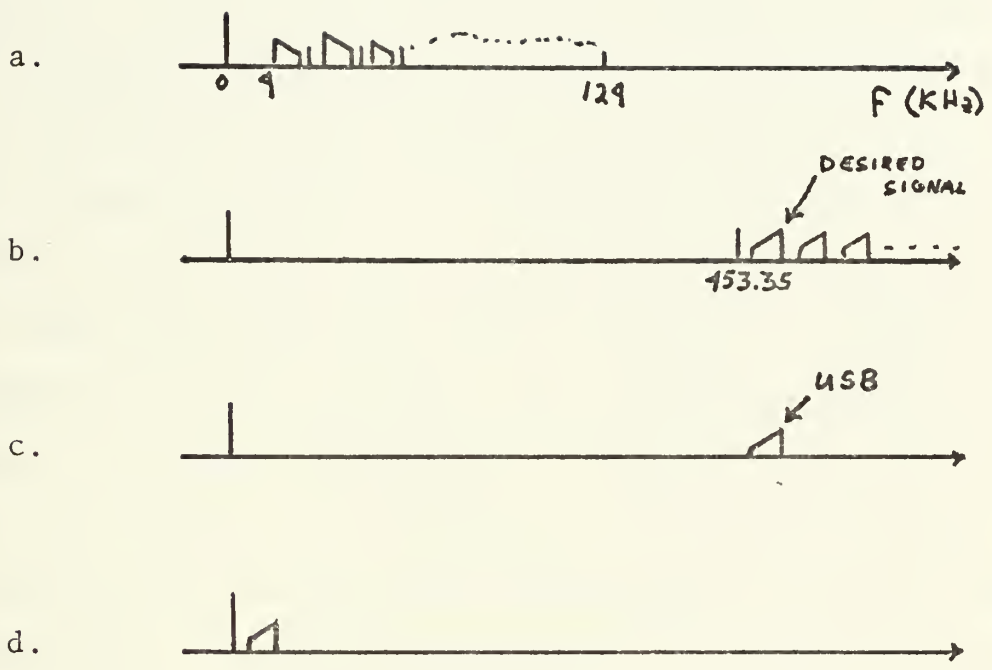


Figure 3. Receiver frequency translation operations, a. Receiver input signals, b. Difference frequencies in balanced modulator, c. Output of mechanical filter, d. Output of receiver (original band-limited signal).

of the injected carrier. It is reconstructed from the base-band signal in the balanced modulator. The carrier pick-off filter amplifies the reconstructed carrier, rejects unwanted frequencies, and feeds the carrier to a phase detector where the receiver carrier frequency is also inputted. The difference frequency between the reconstructed and receiver carrier frequency is amplified by an operational amplifier which is directly coupled to a voltage-controlled channel oscillator. Since the reconstructed carrier is a product of the input signal and the channel oscillator, a change in the channel oscillator frequency will change the reconstructed carrier frequency. The output of the phase detector will change until it drives the difference between the two carrier frequencies (reconstructed and receiver) to zero. When the difference is zero, the output of the phase detector will be a constant and the VCO frequency will not change. This is effectively a phase-locked loop.

E. SIGNALLING

When the circuit is seized by the user, a -48 volt supply is enabled. This supply permits the carrier to be inserted into the circuit. Signalling is accomplished by interrupting the carrier. On the receiving end the carrier amplified by the carrier pick-off filter is used to operate a relay. The bandwidth of the filter is wide enough to permit standard dial pulses at 10 to 12 pulses per second.

V. DESIGN

A. TRANSMIT

The voice frequencies enter the transmitter input either balanced or unbalanced matched to a 600 ohm impedance. (See Figure 7.) An emitter follower is used for isolation between the balanced modulator and input. Capacitor C_3 is used as an RF ground into the balanced modulator which is a series-fed ring modulator. The carrier is inputted into the balanced modulator through a potentiometer for balance so that it may enter the mechanical filter exactly out of phase and be suppressed. A variable capacitor is used for reactive balance. In the balanced modulator opposite diodes conduct on alternating half cycles at the carrier frequency. The carrier is modulated by the input signal producing sidebands due to the nonlinear nature of the diodes. The carrier is suppressed at the input of the mechanical filter, but the sidebands produced in the balanced modulator combine in a push-pull manner at the input to the mechanical filter to double their amplitude. (See Appendix A.)

The input and output capacitors of the mechanical filter are used for impedance matching to properly tune the mechanical filter. It was fortunate the mechanical filter used could accommodate the balanced input. Otherwise, a transformer or differential amplifier would have been required to furnish the necessary phase relationships. A great deal of effort was made to avoid using transformers wherever possible because of their relatively high cost.

Following the mechanical filter is an amplifier to drive the second balanced modulator and a direct coupled emitter follower to provide isolation and a low impedance input to the balanced modulator. A controlled amount of carrier is injected at the base of the emitter follower. The USB which has been passed by the mechanical filter and the injected carrier are the inputs to the second balanced modulator. While similar to the first balanced modulator, there are a few differences from the first balanced modulator. A channel frequency is inputted instead of the carrier frequency in order to place the channel in its position in the frequency domain. To avoid a wide-band transformer a differential amplifier is used to provide the necessary phase relationships for channel frequency suppression. This was felt necessary to lessen output filter requirements. Following the differential amplifier is a low-pass filter to suppress frequencies greater than 124 Khz. The output impedance of the last stage is 600 ohms. A 28 dB Attenuator follows to provide the necessary -29dBm output required. If desired, a potentiometer could be added to the last stage's emitter for use as an output gain control.

The oscillators used are Clapp crystal oscillators for high frequency stability. (See Figure 9.) Variable capacitors are used to tune the crystal to the correct frequency. Emitter followers isolate the oscillators from other circuits. The basic configuration of the oscillators is shown in the carrier oscillator. The channel oscillator is a voltage-controlled crystal oscillator (VCXO) using a variable

capacitance diode. DC voltage through the varicap is isolated from the biasing network of the oscillator transistor by the crystal and a blocking capacitor. The DC voltage across the varicap used to warp the crystal is controlled by the synchronization circuitry.

B. RECEIVE

The baseband signals enter the receiver matched to a 600 ohm impedance. They are amplified by a two transistor feedback amplifier. (See Figure 8.) This amplifier feeds the baseband to the balanced modulator with a low impedance. The balanced modulator is similar to the first balanced modulator in the transmitter except that the channel frequency is injected here. The injected carrier and the USB are reproduced. One side of the balanced modulator is used to feed the reconstructed carrier to the carrier filter. Output balancing of the mechanical filter is accomplished with a potentiometer and a variable capacitor as before. The USB passed through the mechanical filter is amplified and mixed with the carrier frequency to recover the original band-limited signal. The emitter-base junction is used as the nonlinear element for mixing. A low-pass filter follows to attenuate frequencies greater than 4 Khz. The audio signal then enters the three stage amplifier. It has gain control and an output impedance of 600 ohm for impedance matching.

C. SYNCHRONIZATION

The recovered carrier from the first balanced modulator is fed to the carrier filter. A unity gain amplifier shifts

the phase of the signal 180°, and the signal and the inverted signal are fed to point A on Figure 10. For most frequencies the impedance path is high through both paths and cancellation occurs when the two signals are added out of phase. At the carrier frequency, however, the crystal offers a low impedance and an imbalance is created at point A. Since the crystal Q is very high, the bandwidth of the filter is just wide enough (when properly balanced) to pass the carrier and signalling pulses. Point A is the input to the three stage amplifier where the carrier is amplified with adjustable gain. The output of the carrier pick-off filter is applied to the phase detector. See Figure 9.

The carrier from the master oscillator is the other input to the phase detector. It uses a low cost 455 Khz center-tapped IF transformer to split the phase of the carrier oscillator frequency. With the reconstructed carrier and carrier oscillator frequencies in phase, the output of the phase detector is a constant. If the two frequencies are slightly different, the difference frequency appears at the input to the integrated circuit. The difference frequencies should be small, and the time constant of the phase detector is comparatively long as a result.

The output of the phase detector is directly coupled to a CA 3015A operational amplifier. Potentiometer R_8 controls the necessary offset voltage on the operational amplifier for maximum voltage swing. The CA 3015A (see Appendix D) is biased for operation from a single supply and has a

low frequency cutoff to prevent oscillations due to its high gain configuration.

The output of the op-amp is directly coupled to the voltage-controlled channel oscillator. The op-amp's output provides a reverse bias on the variable capacitance diode to vary the diode's capacitance and hence the frequency of oscillation. The varicap used was a silicon Motorola MV837. It has a nominal capacitance of 56 pico-farads with four volts reverse bias and tuning ratio compared with 25 volts of 2.12 typically. As the control voltage increases, the capacitance of the varicap decreases to vary the frequency of oscillation. As the frequency of the channel oscillator changes, the reconstructed carrier changes, and the output of the phase detector also changes. The reconstructed carrier will be changed by the channel oscillator till the output of the phase detector is a constant. This occurs when the reconstructed carrier and the signal from the carrier oscillator are in phase. When this occurs the output frequencies of the receiver will be exactly the same as those transmitted.

D. SIGNALLING

When the circuit is seized by the user, a -48 volts DC is applied to point B on Figure 7. This places the base of the signalling transistor at -24 volts to turn the transistor off and make point C a high impedance. This allows the carrier to be injected into the transmitter circuitry. When the -48 volts is interrupted for signalling pulses, the base

of the signalling transistor goes positive with respect to the emitter and the transistor saturates. This makes point C a low impedance and prevents the carrier from being injected. Injection level is provided through potentiometer R_{14}. A test switch is provided to manually interrupt the carrier.

In the receiver the carrier is detected from the output of the carrier filter (see Figure 10). The carrier is amplitude detected which turns on transistor Q_6. The collector current operates a relay. With the carrier absent, the transistor is off and no current flows through the relay.

VI. RESULTS AND CONCLUSIONS

A single complete channel was built and tested in the laboratory. With available crystals it was possible to test the highest channel and the two lowest channels. Combinations of these were used to test crosstalk between adjacent channels and between the high and low channels.

Distortion measurements were made using the Hewlett Packard HP331A Distortion Analyzer and the Hewlett Packard HP302A Wave Analyzer. The highest channel had 1.5% total harmonic distortion and the low channel had 1.45% total harmonic distortion with a 700 Hz test tone. Distortion was constant with frequency across the passband. The second harmonic was 37 dB below the fundamental and the third harmonic was down greater than 65 dB for both channels.

Crosstalk between the first and last channels was greater than 42 dB below in-band signals. Crosstalk between the first and second channels was only 38 dB below in-band signals. These values of crosstalk were due principally to high frequency leak between the transmitter and receiver. More effective RF shielding and additional filtering in the transmitter could be used to reduce this to 50 dB below in-band signals.

Tuning a channel merely involved tuning the crystals till the system locked in phase. It was possible to obtain a lock range of 33 cycles with one set of crystals and 19 cycles with another set. This indicates that proper selecti n

of crystals can insure a larger lock range. A lock range of 38 cycles was obtained when two oscillators were phase-locked. With crystals having a tolerance of .002%, a worst case would indicate a frequency difference between the input and output frequencies of approximately 40 Hz. The crystal oscillators could be retuned to obtain phase-lock in such a case.

The proposed system is believed to be both competitive in cost and performance with other systems. It takes up little rack space. Repair is facilitated through the use of plug in boards, and channels can be added easily as needed.

APPENDIX A: PRODUCTION OF DOUBLE SIDEBAND

By taking an RF carrier, ω_{c1} and a modulating signal, ω_s, and applying them to a nonlinear device such as a diode, one can get as the input to two diodes:

$$e_1 = E_c \sin\omega_c t + E_s \sin\omega_s t$$

$$e_2 = E_c \sin\omega_c t - E_s \sin\omega_s t.$$

Since diodes are nonlinear devices, their current can be represented by a power series:

$$i_d = a_0 + a_1 e + a_2 e^2 + \cdots$$

Substituting e_1 and e_2, one gets:

$$i_{d1} = a_1 E_c \sin\omega_c t + a_1 E_s \sin\omega_s t + a_2 E_c^2 \sin^2\omega_c t$$

$$+ 2a_2 E_c E_s \sin\omega_c t \sin\omega_s t + a_2 E_s^2 \sin^2\omega_s t$$

$$i_{d2} = a_1 E_c \sin\omega_c t - a_1 E_s \sin\omega_s t + a_2 E_c^2 \sin^2\omega_c t$$

$$- 2a_2 E_c E_s \sin\omega_c t \sin\omega_s t + a_2 E_s^2 \sin^2\omega_s t.$$

In a balanced modulator the output voltage, E_0, is proportional to the difference between these two currents, or:

$$E_0 \alpha 2a_1 E_s \sin\omega_s t + 4a_2 E_c E_s \sin\omega_c t \sin\omega_s t.$$

One notices that the carrier frequency term has cancelled out. This equation can be expanded by trigonometric identity giving:

$$E_0 \alpha 2a_1 E_s \sin\omega_s t + 2a_2 E_c E_s \cos(\omega_c - \omega_s)t$$

$$- 2a_2 E_c E_s \cos(\omega_c + \omega_s)t.$$

This final equation contains the original signal, a band of lower side frequencies called a sideband, and an upper sideband. To produce single sideband one of the sidebands is selected and everything else is rejected. In this system the upper sideband is selected using a mechanical filter.

APPENDIX B: DETERMINATION OF SYSTEM FREQUENCIES

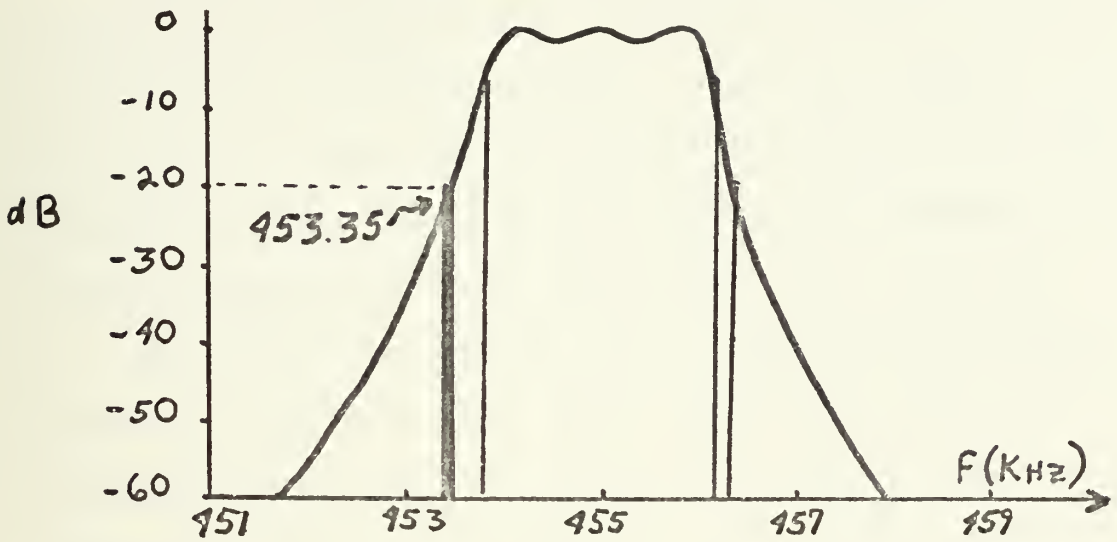


Figure 4. Frequency response of mechanical filter.

In this multiplex system it was desired to utilize the mechanical filter for sideband selection. From the mechanical filter specifications, the system crystal frequencies were chosen which used the filter's characteristics to best advantage-and which placed the channels in their proper positions in the frequency domain.

The frequency response of the mechanical filter is pictured in Figure 4 from its specifications. Vertical lines indicate the 6 dB and 20 dB bandwidths.

The carrier is suppressed by the balanced modulator (up to 50 dB) and then further rejected by the mechanical filter. It is common practice to place the carrier frequency at the -20 dB point on the filter's characteristic. From the drawing in Figure 4, this amounts to 1.65 Khz below the center frequency of 455 Khz to pass the upper sideband. This frequency is 453.35 Khz and is the crystal carrier frequency.

For the channel crystals frequency placement must be such that the channels will be placed in their proper position in the frequency domain. The first channel was chosen to be 8 Khz - USB. For the N^{th} channel the frequency was (4N+4) Khz - USB. Since there were 30 channels planned, the 30 channel was: ((30)+(4)+4) Khz - USB = 124 Khz - USB.

To obtain the channel crystal frequency the channel frequency was added to the carrier frequency, which, for the N^{th} channel amounted to 457.35 + 4N Khz. The process of frequency translation to accomplish the frequency division multiplexing is shown in Figure 2 and Figure 3.

APPENDIX C: SPECIFICATIONS OF THE MECHANICAL FILTER

BACKGROUND:

Mechanical filters, like crystal and L-C filters, are used in a large number of applications such as sideband selectors because of their excellent selectivity, which, through proper design, is retained under widely varying environmental conditions. Their excellent selectivity depends largely on the high Q of mechanical resonators. Their Q is on the order of 10,000 or 50 to 100 times the Q of L-C resonators. The high Q permits choice of higher center frequencies for mechanical filters having the same bandwidth and shape factor as an L-C filter. Mechanical filters have been designed with center frequencies as high as 1 Mhz and as low as 60 Khz. Their design is not limited by this range, but they are most practical within it.

Mechanical filters, like crystal filters, employ resonant mechanical vibration to obtain their selectivity, but contrary to crystal filters which use electrical coupling, mechanical filters use mechanical couplers to transfer vibrations between resonators. To provide coupling between the mechanical elements and the electric circuit, transducers are located at each end of the filter structure. Of the many possible configurations in mechanical filters, three types are most common. One has flat rectangular plates that are connected by fine wires in a type of ladder structure. Another uses a cylindrical rod with alternate necks

and slugs which may be utilized in either the longitudinal or torsional mode of vibration. The third type of mechanical filter employs flat disks coupled by connecting wires.

The selectivity or shape factor of the mechanical filter determines the number of resonators. Fewer disks result in a wider fractional bandwidth for a given shape factor. Response variation across the passband is a function of many variables such as variations in disk tuning, coupling, terminating impedance, and resonating element Q. The passband ripple increases with the number of disks in addition to also being a function of the type of transducer. The electrical transducer causes the principal loss in the filter since very little loss occurs in the mechanical system because of high resonator Q's.

SPECIFICATIONS OF TYPE F455FA-27 COLLINS MECHANICAL FILTER

Center frequency	455 Khz	Nom.
Bandwidth @ 3 dB	2.26 Khz	Min.
Bandwidth @ 6 dB	2.7 Khz	Min.
Bandwidth @60 dB	6.2 Khz	Max.
RV	3.0 dB	Max.
Source Impedance		
parallel resonance	50 k ohms	Min.
series resonance	500 ohms	Max.
Load Impedance		
parallel resonance	50 k ohms	Min.
series resonance	500 ohms	Max.
Resonating capacity		
input	130 ± 20 pf.	
output	130 ± 20 pf.	
Signal input level	5.0 $\overline{V}$ RMS	Max.
DC Current	2.0 ma.	Max.
DC Voltage	100 V DC	Max.

To obtain full advantage of the mechanical filter's selectivity, a common ground connection and effective shielding between input and output are needed.

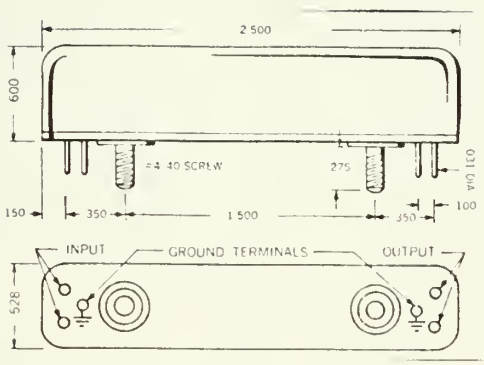
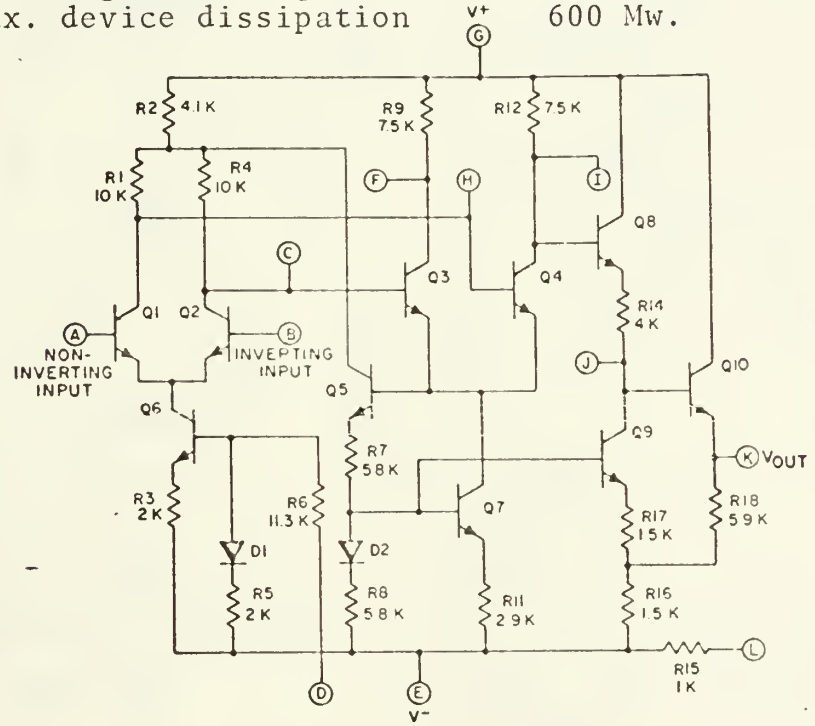


Figure 5. Dimensions of the F455FA-27.

APPENDIX D: SPECIFICATIONS OF THE RCA CA3015A

Open loop voltage gain	50 dB	typ.
Common-mode rejection ratio	103 dB	typ.
Input impedance	10 k ohms	typ.
Input offset voltage	1 mv.	typ.
Input offset current	0.5 ua.	typ.
Input bias current	4.7 ua.	typ.
Static power drain at ± 12 V.	175 mw.	
Operating temperature range	-55' C to 125'C	
Max. signal voltage	-8V to +1 V	
Max. device dissipation	600 Mw.	



All resistance values in ohms unless otherwise specified.

Figure 6. Schematic of CA3015A.

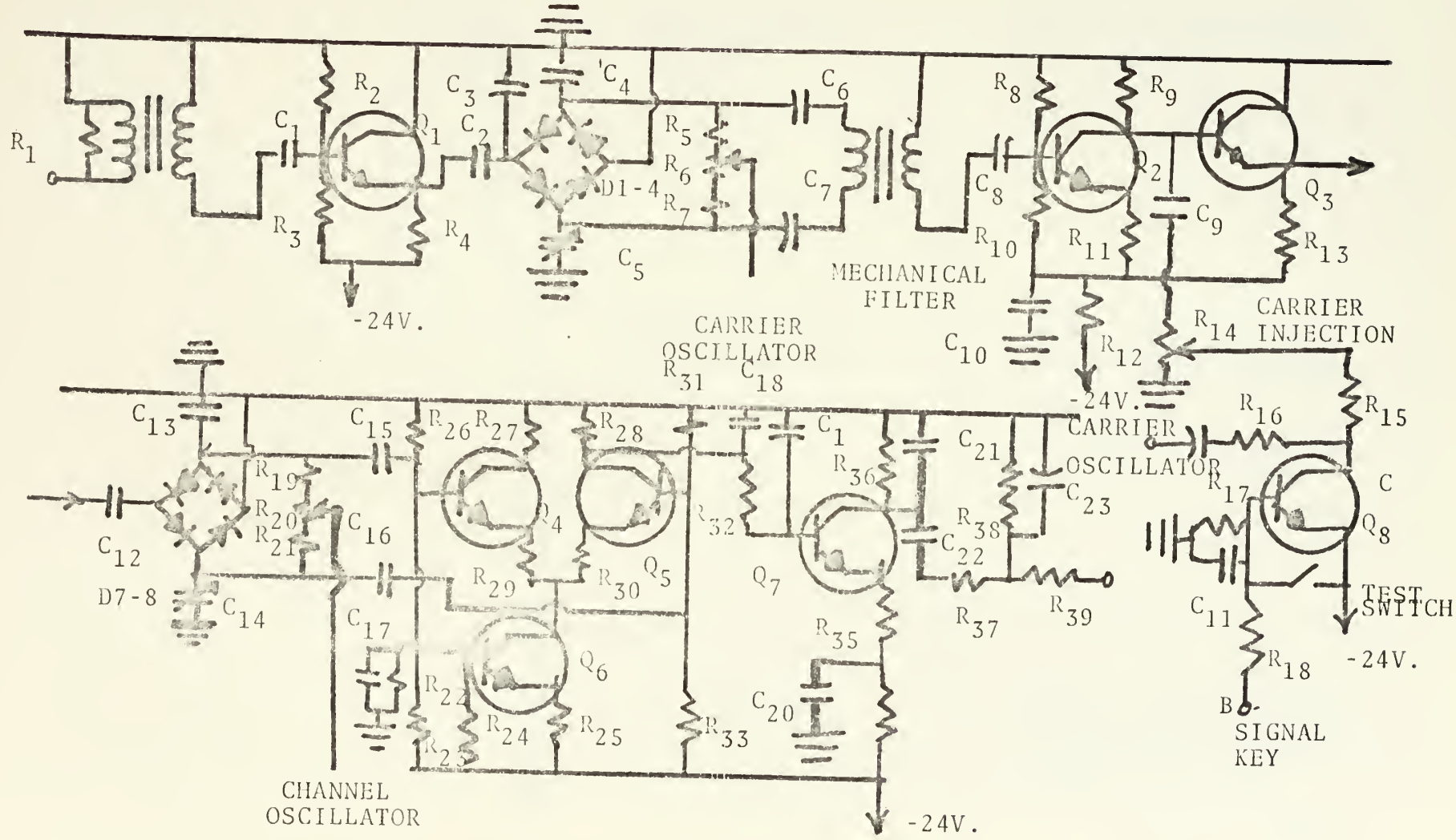


Figure 7. Transmitter Schematic.

Parts List for Figure 7

R1 620	R14 10 k pot.	R27 6.8k
R2 47k	R15 10 k	R28 6.8k
R3 36k	R16 10 k	R29 270
R4 680	R17 10 k	R30 270
R5 270	R18 10 k	R31 100 k
R6 100 pot.	R19 1 k	R32 1 k
R7 270	R20 200	R33 100 k
R8 47 k	R21 1 k	R34 2.2k
R9 4.7 k	R22 100 k	R35 620
R10 2.7 k	R23 100 k	R36 620
R11 270	R24 12 k	R37 510
R12 100	R25 680	R38 91
R13 3.6	R26 100 k	R39 510

All resistors 5% and ohms except as noted

C1 .47	C10 10	C19 100 pf.
C2 .47	C11 .47	C20 1
C3 .01	C12 .1	C21 .002
C4 27pf.	C13 27 pf.	C22 .1
C5 5-30 pf.	C14 1-25 pf.	C23 .004
C6 270 pf.	C15 .1	
C7 270 pf.	C16 .1	
C8 130 pf.	C17 .001	
C9 .01	C18 100 pf.	

All capacitors microfarads except as noted

T1 Microtran MT1FB
Q1-8 2N5172
D1-8 1N126

Mechanical Filter F455FA-27

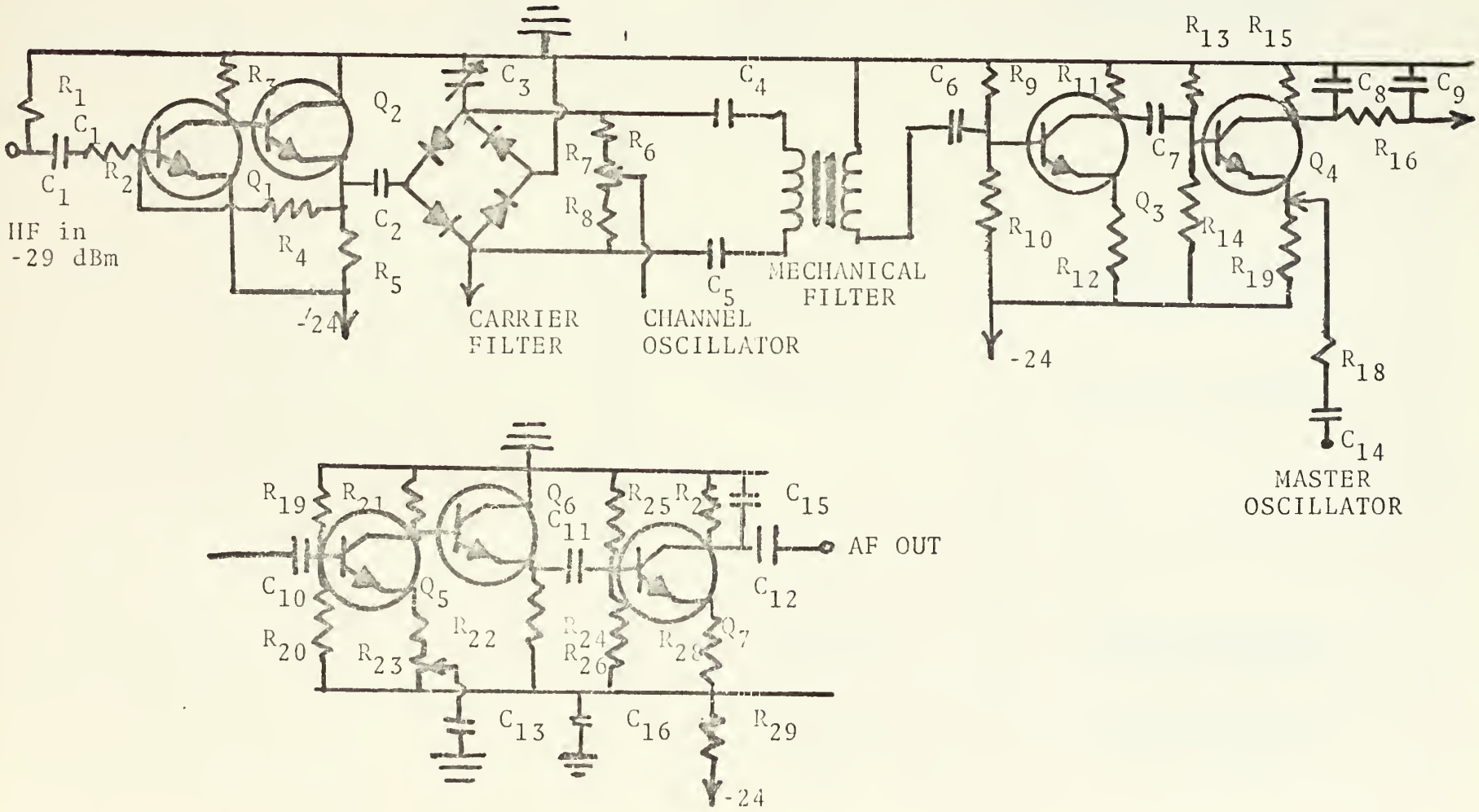


Figure 8. Receiver Schematic.

Parts List for Figure 8

R1	680	R11	4.7k	R21	1.2k
R2	20k	R12	270	R22	10
R3	5.6k	R13	47k	R23	500 pot.
R4	220k	R14	4.7k	R24	3.9k
R5	4.7k	R15	2.7k	R25	22k
R6	270	R16	1k	R26	3.3k
R7	100 pot.	R17	2.7k	R27	620
R8	270	R18	1.2k	R28	100
R9	47k	R19	100k	R29	68
R10	2.7k	R20	47k		

All resistors 5% and ohms except as noted

C1	.1	C7	.015	C13	1
C2	.1	C8	.02	C14	.01
C3	1-25 pf.	C9	.01	C15	.02
C4	270 pf.	C10	.47	C16	10
C5	270 pf.	C11	.47		
C6	130 pf.	C12	.47		

All capacitors microfarads except as noted

D1-4 1N126
Q1-7 2N5172
Mechanical Filter F455 FA-27

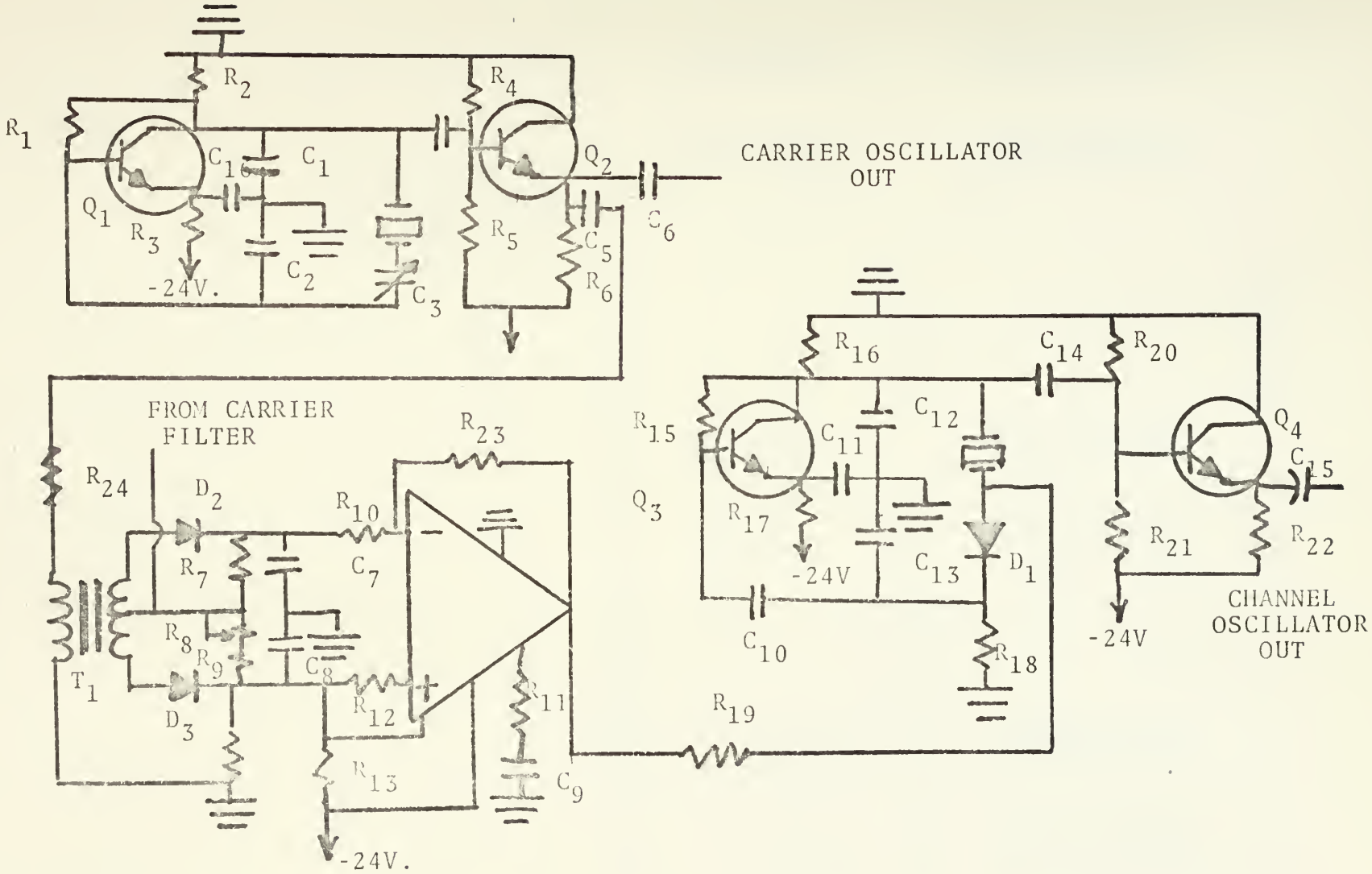


Figure 9. Phase Detector. Carrier and Channel Oscillator Schematic.

Parts List for Figure 9

R1	470k	R9	4.7k	R17	1.2k
R2	36k	R10	100	R18	47k
R3	1.2k	R11	22	R19	100k
R4	47k	R12	100	R20	47k
R5	47k	R13	4.7k	R21	4.7k
R6	620	R14	4.7k	R22	620
R7	30k	R15	470K	R23	1 Meg.
R8	10k pot.	R16	36K	R24	100

All resistors 5%, and ohms except as noted

C1	150 pf.	C7	1	C13	.001
C2	.001	C8	1	C14	.01
C3	1-25 pf.	C9	.1	C15	.01
C4	.01	C10	.01	C16	.1
C5	.01	C11	.1		
C6	.01	C12	150 pf.		

All capacitors microfarads except as noted

Q_{1-4}	2N5172
T_1	455 If transformer
IC_1	CA3015A
D_1	MV837
D_{2-3}	1N126

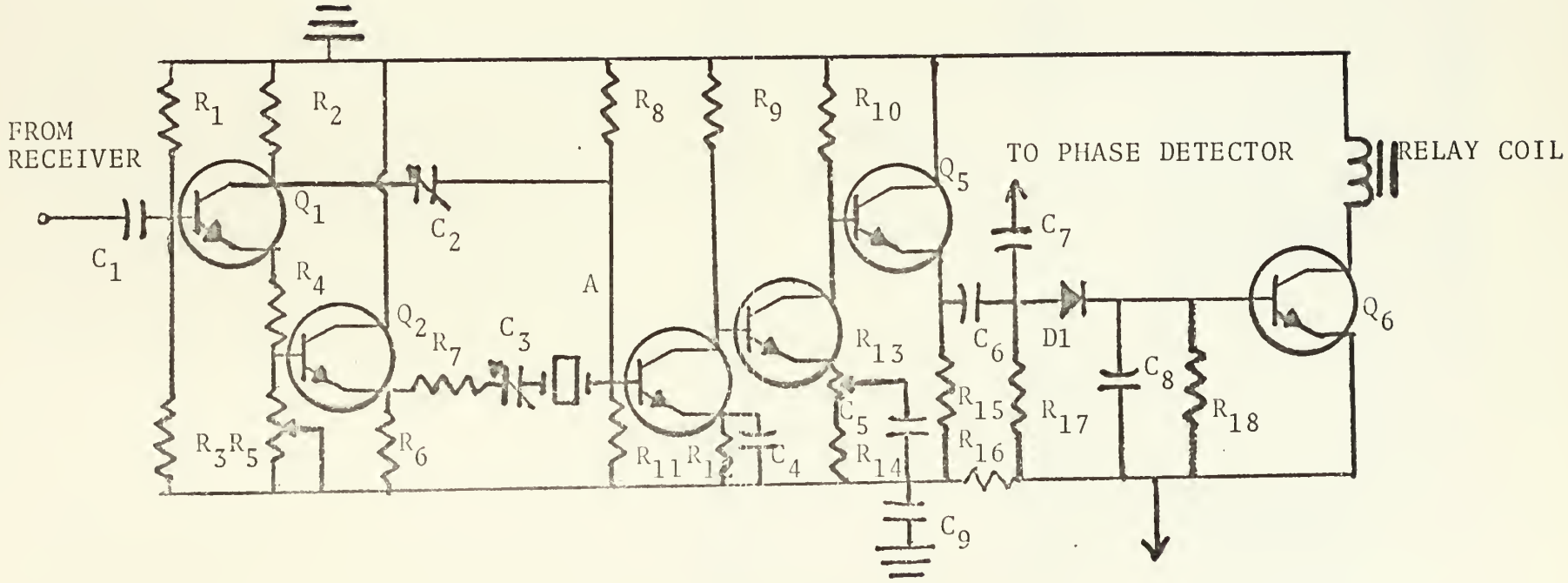


Figure 10. Carrier Filter Schematic.

Parts List for Figure 10

R1	100k	R8	100k	R13	10k pot.
R2	6.8k	R9	10k	R14	47k
R3	47k	R10	22k	R15	18k
R4	5.6k	R11	47k	R16	680
R5	10k pot.	R12	6.8k	R17	1k
R6	6.8k	R13	10k pot.	R18	10k
R7	6.8k	R14	47k		

All resistors 5% in ohms except as noted

C1	.047	C6	.1
C2	1-25 pf.	C7	.1
C3	1-25 pf.	C8	.47
C4	.1	C9	100
C5	.1		

All capacitors microfarads except as noted

Q1-6 2N5172

D_1 1N126

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1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Naval Postgraduate School Monterey, California 93940	UNCLASSIFIED
	2b. GROUP

3. REPORT TITLE

A LOW COST SINGLE SIDEBAND MULTIPLEX SYSTEM

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Master's Thesis; September 1971

5. AUTHOR(S) *(First name, middle initial, last name)*

Guy R. Knieriem

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
September 1971	54	8

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
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13. ABSTRACT

A thirty channel low cost single sideband multiplex system is presented. This design is specifically tailored for microwave communications by small businesses desiring inexpensive, high quality communication links. One channel was built and tested in the laboratory and the results are included. A major factor in the low cost of this system without compromising performance was the availability of inexpensive mechanical filters. Synchronization is a major feature of this system using injected carrier to maintain phase-lock.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Single Sideband Multiplex						
Phase-Locked Loops						
Signalling						
Mechanical Filters						
Voltage Controlled Crystal Oscillators (VCXO)						

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